

## THE SURVIVAL RATE OF EJECTED TERRESTRIAL PLANETS WITH MOONS

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*Draft version February 1, 2008*

### ABSTRACT

During planet formation, a gas giant will interact with smaller protoplanets that stray within its sphere of gravitational influence. We investigate the outcome of interactions between gas giants and terrestrial-sized protoplanets with lunar-sized companions. An interaction between a giant planet and a protoplanet binary may have one of several consequences, including the delivery of volatiles to the inner system, the capture of retrograde moons by the giant planet, and the ejection of one or both of the protoplanets. We show that an interesting fraction of terrestrial-sized planets with lunar sized companions will likely be ejected into interstellar space with the companion bound to the planet. The companion provides an additional source of heating for the planet from tidal dissipation of orbital and spin angular momentum. This heat flux typically is larger than the current radiogenic heating of the Earth for up to the first few hundred million years of evolution. In combination with an atmosphere of sufficient thickness and composition, the heating can provide the conditions necessary for liquid water to persist on the surface of the terrestrial mass planet, making it a potential site for life. We also determine the possibility for directly detecting such systems through all-sky infrared surveys or microlensing surveys. Microlensing surveys in particular will directly measure the frequency of this phenomenon.

*Subject headings:* planets and satellites:formation–astrobiology–methods:N-body simulations

### 1. INTRODUCTION

Binary protoplanets of terrestrial mass and lower may be common–large Kuiper belt objects in particular seem to have a high fraction of satellites that formed through giant impacts much in the same way as the Earth/Moon system (Canup 2004, 2005). Three of the four known large KBOs (Pluto, 2003UB313, and 2003EL61) contain satellites, with Pluto/Charon having a mass ratio closest to 1 (Brown et al. 2006). Assuming similar densities and albedos between parent and body and based on the relative brightnesses, the other two binary KBOs have mass ratios similar to the Earth/Moon system (Brown et al. 2006). Since these objects and the Earth/Moon system exist, three body interactions need to be studied in the context of planet formation.

Giant impacts, the main process for forming lunar mass moons to terrestrial planets, occur 1-2 times over the course of terrestrial planet formation simulations with enough angular momentum to form the Earth-Moon system (Agnor et al. 1999; Chambers 2001). The value of this angular momentum is dependent on the angle of impact, the mass of the impactor, and ratio of impact speed to escape speed. A range of parameters can create a situation where Earth-Moon analogues are formed. This range is limited for the specific case of the Moon due to other constraints such as a lack of iron relative to the Earth (Jones & Delano 1989), but many constraints are relaxed for an impact that creates a generic moon of lunar mass, allowing for a reasonable probability that the Earth/Moon system is mediocre and analogues should be present in a non-negligible fraction of planetary systems.

Even though there are examples of binarity in the ter-

restrial planet region and in the Kuiper belt, it is not clear whether conditions exist to form Earth/Moon sized systems where giant planets arise. Two scenarios could create a situation where a binary protoplanet may come in close contact with a Jovian planet.

The first is that the binary interacts with a Jovian *in situ* during giant planet formation. The binary would be a leftover from oligarchic growth, similar to the scenario proposed by the formation of Uranus and Neptune through scattering with Jupiter and Saturn (Thommes et al. 2002). In some cases, oligarchic losers will be ejected to escape speeds. The size distribution of protoplanets in this region is poorly known, but oligarchic growth starts at  $\sim 10^{-5} M_{\oplus}$  and proceeds to a gas accretion runaway growth mass of  $\sim 10 M_{\oplus}$  (Thommes et al. 2003; Pollack et al. 1996). Oligarchic growth in the terrestrial planet region appears to spread from higher density to lower density regions (Kokubo & Ida 2002), which suggests that a size range of oligarchs would be present in the region of 5-10 AU. Leftovers that range from the smallest oligarch mass to ice giant mass are possible (Chiang et al. 2007) and could explain Uranus's peculiar axis of rotation as a result of a giant impact between it and a large late stage leftover (Korycansky et al. 1990; Brunini et al. 2002). The constraints on the size of left-overs at late stages of the Solar System's formation around the region of Neptune places stringent constraints on the maximum size of the planetesimal distribution to sizes much smaller than the Earth, though one time encounters with Mars-like protoplanets are not ruled out (Murray-Clay & Chiang 2006). However, the typical architecture of a planetary system is not well known and the stochastic behavior of oligarchic growth would argue for a wide range of possible outcomes for planetary systems between 5-10 AU, including the presence of terrestrial mass protoplanets (Levison et al. 1998).

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Secondly, forming planetary systems where one or more giant planets migrate to small orbital radii may lead to the ejection of several smaller planets in the process (Raymond et al. 2006). Some ejected planets may have bound companions that are a significant fraction of their host planet's mass. The frequency of such systems and the survival rate of these binary protoplanets during ejection is an interesting open question.

If terrestrial planets are ejected with lunar-sized companions, they may be habitable, despite being deprived of an isolating central star. If an isolated terrestrial planet is ejected with significant atmosphere captured from the parent protoplanetary disk, the planet will have a surface temperature high enough to sustain liquid water (Stevenson 1999).

The presence of the companion will add heat through tidal dissipation of spin and angular momentum, which will augment the heat flux due to radioactive materials in the interior of the planet. Tidal heating has been investigated in the melting of the moon, the vulcanism on Io, and the heating of Europa (Peale & Cassen 1978; Peale et al. 1979; Cassen et al. 1979; Carr et al. 1998). The heating will decay over time, but if life evolves, it could persist for long times below the surface of the larger planet (Laughlin & Adams 2000).

## 2. NUMERICAL SIMULATIONS

To test the frequency of binary protoplanet ejections we have run 2700 numerical simulations using the Mercury integration code (Chambers 1999). We placed a binary protoplanetary system with an Earth mass primary and a lunar mass secondary in Hill unstable orbits relative to a giant planet on a concentric orbit. Hill stability is defined as a system that experiences no close approaches between the constituent planets in the system (Hill 1886; Gladman 1993). We chose initial positions for the terrestrial planet to be between 0.5-1 times the critical Hill radius interior and exterior to the giant planet. Initial eccentricities of the binary protoplanet system were set to 0.05 and inclinations were  $< 5^\circ$ . Initial semi-major axes of the companion's orbit were set to  $30 R_\oplus$ , half the current Moon-Earth separation. Initial Moon-Earth separations would be smaller, but we chose this separation as a compromise between simulation speed and physical reality, as this separation dictates the time step required to accurately integrate the equations of motion. Timesteps were set to  $\sim 8$  days and were adaptable. A system was run for a maximum of  $10^6$  yr but was checked at  $10^4$  yr and  $10^9 r$ . In this way, highly interacting systems that disrupted the binary protoplanets were removed early in the integration. Our criteria for ejection was that the binary protoplanets were bound to each other, but unbound from the central star with a radial distance  $> 15$  AU from the central star. In the simulations, no system was considered ejected unless it passed beyond a radial distance of 5000 AU, so in most cases the ejected binary protoplanets were allowed to evolve for several thousand years beyond the perturbation that ejected the system. Fractional errors in energy and angular momentum were  $\sim 10^{-11}$  but were larger if systems suffered a collision. The highest errors were  $\sim 10^{-8}$ . Figure 1 shows a typical ejection of a protoplanet with a surviving companion.

As a further test of the stability of the simulations we

ran ten long term simulations of an isolated binary protoplanet system to determine if the initial orbit could be stable for  $10^6$  yr, the maximum length of the simulation. We found that in all ten simulations the orbits remained stable for initial eccentricities of  $\sim 0.15$ .

## 3. RESULTS

Of the 2700 simulations, 90, or 3.3% of the interactions resulted in only the Earth being ejected, while 123 or 4.6% of the simulations ended in an ejection of a bound Earth-Moon system. In most cases the eccentricity of the bound Earth/Moon systems increased after ejection. Bound ejections occur through multiple grazing encounters with the Jovian, which is consistent with the perturbations on the Earth/Moon system being less than their binding energy.

An estimation of the tidal dissipation in these ejected systems shows that tidal heating can be as important as radioactive heating. Heating can come from circularization of a satellite's eccentric orbit as well as synchronization between the planet's spin and the satellite's mean motion. Heating rates for circularization are dependent on the eccentricity  $e$ , semi-major axis  $a$ , and mean motion  $n$ :

$$\dot{E}_{circ} = -\frac{63e^2 n}{4\tilde{\mu}Q_p} \left(\frac{R_p}{a}\right)^5 \frac{Gm_s^2}{a}. \quad (1)$$

The variable  $\tilde{\mu}$  is the ratio of elastic to gravitational forces, or the effective rigidity of the planet. The variable  $Q_p$  is the planet's specific dissipation function, and  $R_p$  is planetary radius. Heating for synchronization can be found by the following equation:

$$\dot{E}_{synch} = -\text{sign}(\omega - n) \frac{3k_{2p}}{Q_p} \frac{m_s^2}{m_s + m_p} \left(\frac{R_p}{a}\right)^5 n^2 a^2 (\omega - n) \quad (2)$$

where we assume that the planet's rotational frequency is greater than its mean motion and the rotational period for the terrestrial planet is 10 hr (Murray & Dermott 2000). Median values of eccentricity and semi-major axis of the ejected pairs are 0.13 and  $30 R_\oplus$ , respectively.

We assume two cases, a rocky planet and an icy planet. A protoplanet will fall in between these two cases, depending on where it formed. A rocky planet will be identical to the Earth in mass, radius, density, and rigidity. We take  $k_2=0.299$ ,  $\tilde{\mu}=4$  and  $Q_p=12$  (Murray & Dermott 2000). For an icy body we assume a rigidity of ice of  $4 \times 10^{12}$  dyne  $\text{cm}^{-2}$ , and assuming a density of  $1 \text{ g cm}^{-3}$  for pure water ice, a  $k_{2p}=0.7$  and  $\tilde{\mu}=1$ . We assume a  $Q_p=100$ .

From among the end states of the ejected planets, the maximum heating came from a system with a semi-major axis of  $21 R_\oplus$  and an eccentricity of 0.21, corresponding to a total heating of  $4.2 \times 10^{22}$  ergs/s assuming a rocky planet. This is 100 times larger than current terrestrial radiogenic heating (Stacey 1992). The maximum heating for an icy planet is a factor of five larger. The distributions of heating rates for rocky and icy planets from our simulations relative to the terrestrial radiogenic rate are presented in Figures 2.

We compare these rates to the tidal heating on Io, whose luminosity is  $\sim 10^{21}$  ergs/s (Veefer et al. 1994), or about three times larger than the terrestrial radiogenic heating rate. The highest heating of a rocky planet is

roughly 4% of the total insolation the young Earth experienced from the Sun, assuming a current rate of  $1.5 \times 10^{24}$  ergs s $^{-1}$ . While this heating is small in absolute terms compared to the conditions present on Earth for the formation of life, it does not create an insurmountable barrier for life to form and evolve. The heating would provide energy for maintaining liquid water and forming life on the planet, potentially in localized hot spots where vulcanism or other geothermal processes occur.

Heating decay over time for the terrestrial planet would depend on the change in the planet's rate of rotation ( $\dot{\omega}$ ) and the semi-major axis ( $\dot{a}$ ) due to tidal evolution of the pair. Assuming  $\dot{a} \propto a^{-5.5}$  and  $\dot{\omega} \propto a^{-6}$  (Murray & Dermott 2000), we calculated  $a$  and  $\omega$  as a function of time and determined when  $\dot{E}$  in Equation 2 meets current radiogenic levels. For our best case, we found that the heating from Equation 2 reaches radiogenic heating in 144 Myr for a rocky planet, and 246 Myr for an icy planet. This may be enough time for life to arise and adapt to decreasing temperatures on the planet.

#### 4. DETECTABILITY OF FREE FLOATING EARTHS

Given the uncertainties in the formation rate of binary protoplanets, the number of such objects per star, and the number of planetary systems, we rely on an analogue of the Drake Equation to estimate the space density of ejected terrestrial planets and ejected binary protoplanets. In reality there will be a size distribution of such objects each with different rates, but this will allow us to get an idea of detectability through imaging and microlensing surveys.

$$N = N_\star f_{\text{planets}} n_{\text{planets}} f_{\text{binary}} f_{\text{ejected}} \quad (3)$$

where  $N_\star$  is the number of stars in the Galaxy,  $f_{\text{planets}}$  is the frequency of planetary systems around stars,  $n_{\text{planets}}$  is the number of terrestrial sized protoplanets that are formed in the system,  $f_{\text{binary}}$  is the frequency of protoplanets that have companions, and  $f_{\text{ejected}}$  is the frequency these protoplanets are ejected with their companions intact. With the exception of  $N_\star$  and  $f_{\text{ejected}}$ , these quantities are not known, but can be estimated within an order of magnitude; so a reasonable estimate is possible.

We assume that the fraction of stars that have planets is 50% as a compromise between the minimum of a few percent, which would be the fraction of solar type stars with known planets, and a maximum of one planetary system per star. We assume that the number of terrestrial protoplanets available for ejection is on the order of 10, which is the same order of magnitude of rocky material present in the giant planet region. We assume that there are several contenders to become the eventual large giant planet, and the “losers” form the primary reservoir of unstable protoplanets that will encounter the Jovian. Systems with Jovians that migrate will also play a role, which may help to increase this reservoir.

The fraction of protoplanets that have companions is also unknown, but can be assumed to be roughly 33% based on our own Earth-Moon system and the assumption that our Solar System is mediocre. Considering the frequency of binary asteroids and kuiper belt objects, the frequency is probably no less than a few percent.

With these assumptions, we arrive at a total number of free floating binary planets of  $7 \times 10^8$ , assuming a total of  $10^{10}$  stars in the galaxy. Assuming that these planets are restricted to the galactic thin disk, with a radius of 25 kpc and a scale height of 0.4 kpc, we estimate a space density for these objects of  $9 \times 10^{-4}/\text{pc}^3$ .

To estimate the free floating planets' spectrum, we assume a median heating luminosity of  $5.3 \times 10^{21}$  ergs/s for rocky planets and a Planck spectrum. The flux density will peak at  $\sim 77\mu\text{m}$ , so one would require an all-sky IR survey sensitive to  $\sim 0.3$  nano-Jy to detect  $\sim 100$  objects out to a distance of 50 pc. The background limited sensitivity of Hershel's PACS instrument is predicted to detect 3mJy sources at  $\sim 68\mu\text{m}$ . A similar sensitivity would require a  $> 750\text{m}$  size primary to detect a free floating planet in 1 hour of observing. However, the closest of these objects will be 5 times closer and thus 25 times brighter with a large proper motion. Provided it can be resolved from the IR background due to galaxies, one to a few detections could be made with less stringent restrictions. Thus, we consider the above to be a conservative estimate of what could be detected.

In the case of microlensing, proposed next generation surveys will be sensitive to free floating terrestrial planets (Bennett & Rieh 2002). In most cases, microlensing events of planets in orbit around stars have a degeneracy between mass, distance, and proper motion. This degeneracy is fortunately broken given certain observational setups which allow the other parameters to be measured (Han et al. 2004, 2005). Binary protoplanets with separations similar to those studied in this work should be easily detectable given that the orbits reside well within the Einstein ring radius of the host planet (Bennett & Rieh 2002). Simulations of detection frequencies for next generation missions assuming a free floating planet frequency of 1-10 free floaters per star result in  $\sim 10$ -100 detections of earth mass free floating planets for the mission (Bennett & Rieh 2002). Assuming a third of free floating planets started out with companions and  $\sim 5\%$  of those were ejected with a companion intact, there would be a 1-2% chance that any free floater would have a lunar mass companion.

#### 5. OTHER IMPLICATIONS

There are other implications that deserve further study. A significant fraction of stable binary systems at the end of our simulations were at large radii ( $\sim 1\%$ ), but had not been ejected. They will either continue to be on wide orbits, or they will eventually be ejected on timescales longer than 1 Myr. If some of these systems remain bound to the central star, they may become rogue planets that periodically perturb planetesimals at larger orbital separations, akin to the “Planet X” hypothesis presented to explain periodic extinctions on the Earth (Whitmire & Matese 1985). For binary protoplanets, this occurrence appears to be rare. It will be more common for singular protoplanets, but we did not follow this specific outcome.

Of the 2700 simulations 12% of the lunar companions were captured into resonant retrograde orbits with the Jovian planet. Tidal dissipation between the companion and the Jovian could be enough to capture the companion into a stable bound orbit. Three body interactions have been pointed to as a formation mechanism

for the retrograde Neptunian satellite Triton, and could explain how the Saturnian satellite Phoebe could have been captured from the outer solar system into its current elliptical and retrograde orbit (Johnson & Lunine 2005; Agnor & Hamilton 2006).

Several simulations had remnant protoplanets that were kicked into eccentric orbits that strayed into the inner system, with periastrons that approached 1.5 AU, thus providing a mechanism to bring volatile rich protoplanets into the inner system. The delivery of volatiles from further out in the proto-planetary disk seems to be a natural outcome of planet formation (Morbidelli et al. 2000; Raymond et al. 2004).

Tidal heating is greater around planets that are more massive, especially terrestrial companions to gas giants or brown dwarfs. These objects will either be large oligarchic losers or isolated objects that formed with large circumstellar disks (i.e. Luhman et al. 2005). The heating these objects feel will be more substantial than that felt for the planets in this study and could be longer lasting if multiple companions are formed whose mutual gravitational interactions provide eccentricity perturbations. Each of these larger planets will have respective habitable zones where tidal heating replaces insolation as the dominant heat source for liquid water (Reynolds et al.

1987; Scharf 2006). These objects will also be detectable through microlensing.

Since all of the ejected binary protoplanets experience heating greater than that currently experienced by the Earth, they will require thinner atmospheres than those considered by Stevenson (1999). From Stevenson (1999), the surface temperature of a protoplanet with an atmosphere is

$$T_s \sim 425\chi^{\frac{1}{12}} \left( \frac{f_{atm}}{0.001} \right)^{0.36} \quad (4)$$

where  $\chi$  is the ratio of tidal heating to the current radiogenic heating of the Earth,  $f_{atm}$  is the fraction of the planetary mass that is in the form of an atmosphere. To maintain a surface temperature of 270 K with radiogenic and median tidal heating together requires two times less atmosphere by mass than radiogenic heating alone. Since tidal heating decays rapidly, radiogenic heating will be an important mechanism for sustaining an established biosphere for longer time scales.

The authors thank J. Chambers for helpful discussions on oligarchic growth and the referee, D. Stevenson for suggestions on improving the paper.

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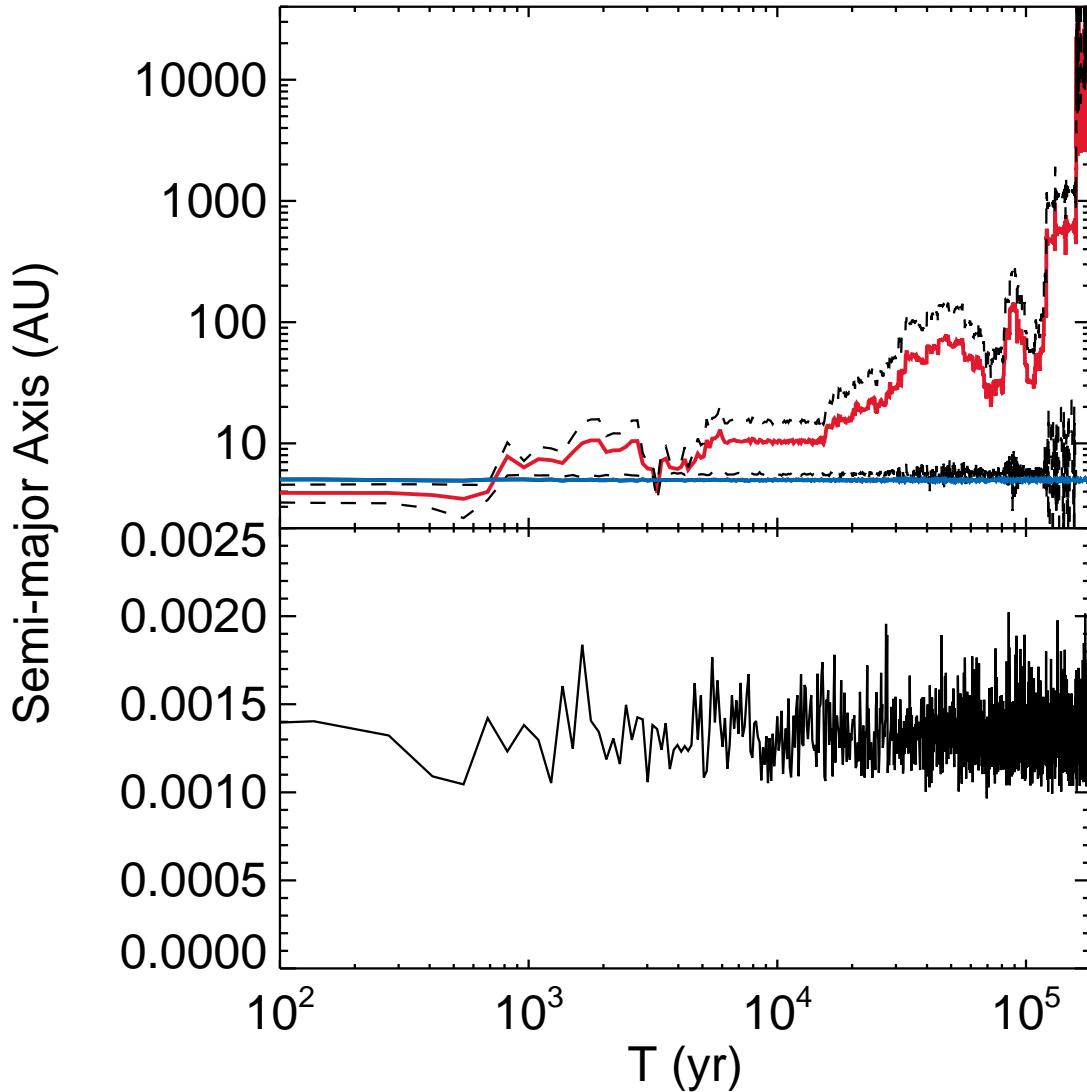


FIG. 1.— (Top) An integration of a binary protoplanet in a Hill unstable orbit with a gas giant. The thick blue curve is the gas giant, while the dashed red curve represents the binary protoplanets. The thin dashed lines represent the periastron and apastron of the binary pair. (Bottom) The same integration but in the rest frame of the terrestrial mass member of the binary protoplanets, showing the semi-major axis of its companion as a function of time. The eccentricity of the companion remains roughly constant at  $\sim 0.15$

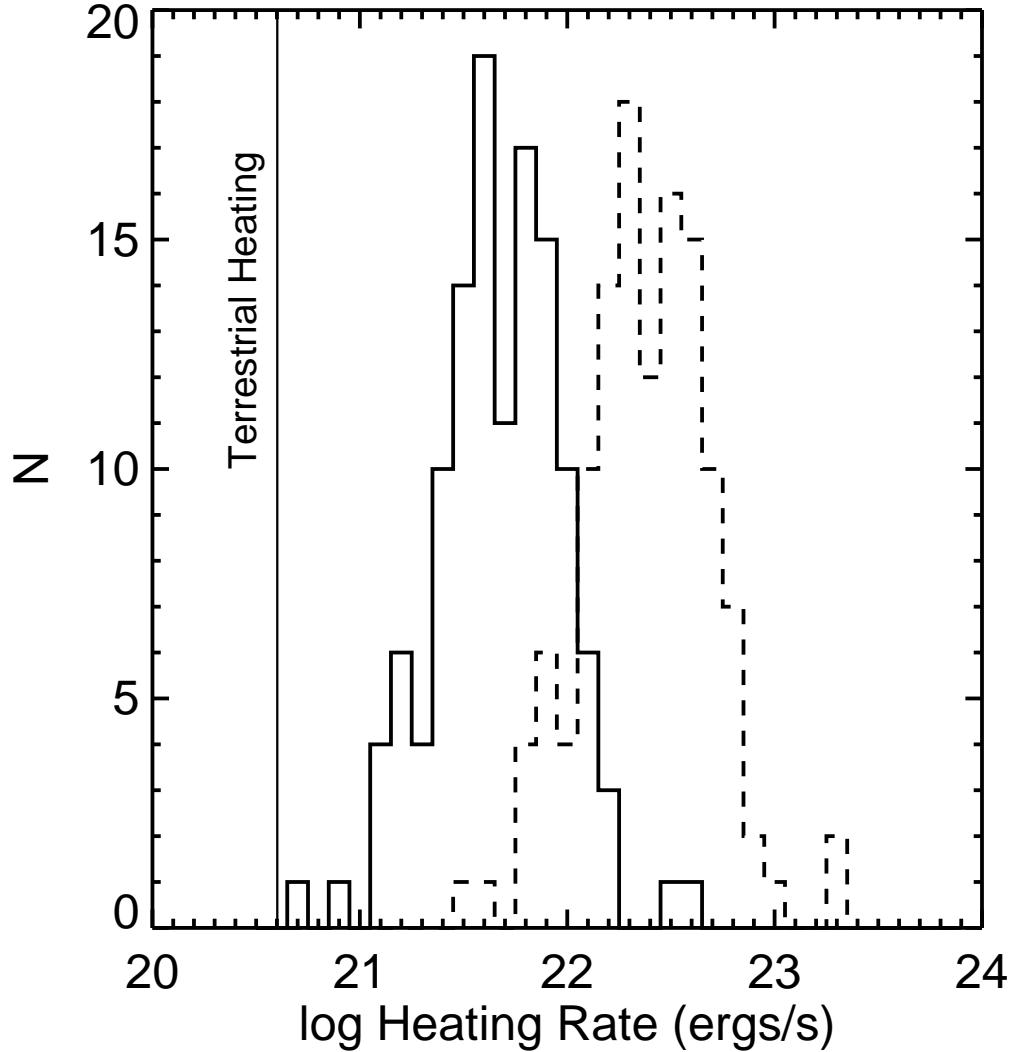


FIG. 2.— The distribution of tidal heating for the 123 ejected binary protoplanets. The solid line curve corresponds to the assumption of rocky planets, while the dashed line corresponds to the assumption of icy planets. The vertical line is the amount of radiogenic heating currently on Earth.